Physics Letters B 679 (2009) 36–40

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Orbital electron capture decay of hydrogen- and helium-like ^{142}Pm ions

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ARTICLE INFO

Article history:
Received 25 March 2009
Received in revised form 29 June 2009
Accepted 10 July 2009
Available online 17 July 2009
Editor: V. Metag

ABSTRACT

The β^+ and orbital electron-capture decays of stored hydrogen- and helium-like ^{142}Pm ions have been measured. So far, such measurements have been performed with only one nucleus, namely ^{140}Pr. The electron-capture decay constant of hydrogen-like $^{142}Pm^{60+}$ ions is about 50% larger than that of helium-like $^{142}Pm^{59+}$ ions, which is in excellent agreement with the previous measurements in ^{140}Pr ions and with new theoretical predictions.

1. Introduction

The development of heavy ion accelerator facilities has enabled the investigation of decay properties of highly-charged ions. One of the motivations is that the atoms in hot stellar plasmas are highly-ionized or even bare, a condition which can be now investigated in the laboratory. In such cases it can be expected that the rates of the weak decay as well as internal conversion are strongly changed compared to neutral atoms. This can have substantial impact on the nucleosynthesis in stars [1]. First experiments were done with in-flight separators by measuring electron conversion rates of Coulomb excited levels in swift highly-charged ions. Significant modifications of the decay rates and a new decay channel, bound-state electron conversion, have been observed [2,3].

Extensive decay studies with highly-ionized nuclides are performed at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt employing a still unique combination of a heavy-ion synchrotron, a projectile fragment separator and an experimental storage ring facilities [4,5]. With these facilities, it is possible to produce, separate, and store for extended periods of time (hours) exotic nuclei with a well-defined number of bound electrons. Basic nuclear properties such as masses and lifetimes are measured by applying the time-resolved Schottky Mass Spectrometry (SMS) [5–8]. The nuclear orbital electron capture (EC) and electron conversion decays are disabled in the absence of orbital electrons. A pure β^+-decay branch has been measured in $^{52}Fe^{26+}$ ions [9] and the half-lives of isomeric states, decaying mainly in the neutral atom via the electron conversion channel, were found to be dramatically prolonged in bare ions [10].

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doi:10.1016/j.physletb.2009.07.019

The largest observed lifetime modifications are due to the bound-state β^- decay, β_b^-. This is a decay channel where the emitted electron can be captured into atomic inner-shell vacancies instead of being emitted into the continuum, like in the conventional β^- decay. This new decay mode β_b^- was for the first time experimentally verified for fully-ionized ^{163}Dy and ^{187}Re nuclei. Neutral ^{163}Dy atoms are stable and become radioactive via β_b^-, when fully ionized, with a half-life of 47 days [11]. Bare ^{187}Re^{75+} ions decay by 9 orders of magnitude faster than neutral ^{187}Re atoms with a half-life of 42 Gyr [12]. A first direct measurement of the branching ratio of continuum and bound-state β^- decay has been done in ^{207}Tl^{81+} ions recently [13].

The data on nuclear decay of hydrogen- (H-like) and helium-like (He-like) ions is still very scarce. Up to now there has been performed only one experiment studying the EC decay of H-like and He-like ^{140}Pr ions [14]. It has been observed that the EC decay rate in H-like ^{140}Pr^{58+} ions is by 50% larger than in He-like ^{140}Pr^{57+} ions. Here we report on the first measurements of the EC decay rates in H-like and He-like ^{142}Pm ions. Also, the pure β^+ decay branch has been measured for fully-ionized ^{142}Pm nuclei. The obtained results confirm the basic findings of Refs. [14,15] and are in excellent agreement with expectations of a newly developed theory [16,17] which takes into account the conservation of the total angular momentum of the nucleus–lepton system.

2. Experiment

The experiment has been performed at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany. The primary beam of ^{152}Sm with an intensity of about $\sim 3 \times 10^9$ particles per spill has been accelerated to the energy of 607.4 MeV/u by the heavy-ion synchrotron SIS [18]. The fast extracted beam (within about 500 ns) impinged on the 2.513 g/cm^2 beryllium production target placed in front of the fragment separator FRS [19]. The projectile fragments emerged from the target with relativistic energies in the forward direction. The fully-ionized, H-like and He-like ^{142}Pm ions were alternatively separated in flight with the FRS (the flight time through the FRS was a few hundred nanoseconds) employing a two-fold magnetic rigidity analysis and atomic energy loss in matter (Bρ–ΔE–Bρ separation method) [19]. For this purpose a 731 mg/cm^2 aluminum energy degrader was employed at the central focal plane of the FRS. A 256 µm niobium foil was installed right after the degrader to achieve an advantageous atomic charge-state distribution. Fully ionized ^{142}Pm^{61+} ions having the largest yield after the production target were transported to the degrader after the first section of the FRS. The final atomic charge-state of ^{142}Pm ions was selected after the niobium foil. The foil was thick enough to assure equilibrium charge state distribution of the emerging ions. To estimate this distribution, we used the GLOBAL code [20] which gives for our exit energy of 400 MeV/u 89.6% of bare ^{142}Pm ions, 10.1% with one bound electron, and 0.31% with two bound electrons.

The mono-isotopic ion beams of ^{142}Pm ions in a selected atomic charge state have been injected into the experimental storage ring ESR [21] and stored in the ultra-high vacuum ($\sim 10^{-11}$ mbar). A combination of the stochastic pre-cooling [22] and electron cooling [23] has been used to reduce the initial velocity spread caused by the nuclear reaction to $\delta v/v \approx 5 \times 10^{-7}$. The stochastic cooling operates at a fixed velocity, corresponding to 400 MeV/u energy. The overall cooling time was about 2 seconds.

The unambiguous identification of cooled ^{142}Pm^{61+}, ^{142}Pm^{60+} and ^{142}Pm^{59+} ions and their decay products has been achieved exploiting the time-resolved Schottky Mass Spectrometry [8,24]. This technique is based on Schottky-noise spectroscopy [25], which is widely used for non-destructive beam diagnostics in storage rings. The stored ions were circulating in the ESR with revolution frequencies of about 2 MHz. At each turn they induced mirror charges on two electrostatic pick-up electrodes, which were part of the resonance circuit. These signals were tiny in comparison to the thermal noise of the electrodes. The 31st harmonic of the sum signal was amplified, mixed down and digitized with 640 kHz sampling rate by a 16-bit ADC. The subsequent Fast Fourier Transform yielded the noise power-density spectra, or, what was the same, the revolution frequency spectra of stored ions. For the present analysis we produced frequency spectra, records, with resolution of about 9.7 Hz per frequency bin, which required 2^{15} data points or 0.1 s of recording time. The details of the data acquisition system and of the data treatment can be found in Refs. [5,8] and references cited therein.

The revolution frequencies provide information about the mass-over-charge ratios of the ions. The area of the frequency peaks is proportional to the number of stored ions, which is the basis for lifetime measurements [9–13,15,26].

The amplitude of a noise-power density spectrum at a given frequency point varies from record to record. It can be shown [27–30] that a relative statistical uncertainty σ_a of the amplitude a is

$$\frac{\sigma_a}{a} = \frac{1}{\sqrt{N_{\mathrm{av}}}}, \tag{1}$$

where N_{av} is the number of averaged records. This uncertainty is also often called random error. In the present analysis we used $N_{\mathrm{av}} = 25$, which means that our amplitudes have uncertainties of 20%, see Eq. (1).

The ^{142}Pm nuclei decay by 96.4% via allowed Gamow–Teller transition ($J^\pi : 1^+ \to 0^+$) to the stable ground state of the ^{142}Nd^{60+} daughter nuclei [31].

In the electron-capture decay the atomic mass changes but the ionic charge state is preserved. The decay causes a sudden increase of the revolution frequency by about 400 Hz (31st harmonics) corresponding to the Q-value of the decay. An example of the measured revolution frequency spectra for the EC decay of H-like ions (^{142}Pm$^{60-} + e^- \to {}^{142}Nd^{60-} + \nu_e$) is illustrated in Fig. 1. In the EC decay a mono-energetic neutrino is emitted, which transfers a small recoil energy of about 90 eV onto the daughter ion. It is cooled down by the electron cooling within less than a second [32]. All daughter ions remain in the acceptance of the ring. It can be seen in Fig. 1 that the intensity of the peak at lower revolution frequency – corresponding to the parent ions ^{142}Pm^{60+} – decreases and that the intensity of the peak at the higher frequency – corresponding to the lighter daughter ions ^{142}Nd^{60+} – increases. Other ion species that might feed the ^{142}Pm or ^{142}Ce ions via radioactive decays or atomic charge exchange reactions have been safely avoided by blocking their closed orbits in the ESR with mechanical slits. Note, that the recoiling nucleus and the emitted electron neutrino, which is not a mass eigenstate of the weak interaction Hamiltonian, are connected by energy and momentum conservation [32]. In the three-body β^+-decay, the atomic charge changes by one unit and the revolution frequency changes by more than 100 kHz (31st harmonics). The corresponding change in the orbit length brings the β^+-decay daughter ions outside the storage acceptance limited by the mechanical slits. This prevented us from a direct measurement of the growth of the β^+-decay daughter ions.

3. Results

The decay constant $\lambda = \ln(2)/T_{1/2}$ of the parent ^{142}Pm nuclei is a sum of three components: the EC decay constant λ_{EC}, the con-

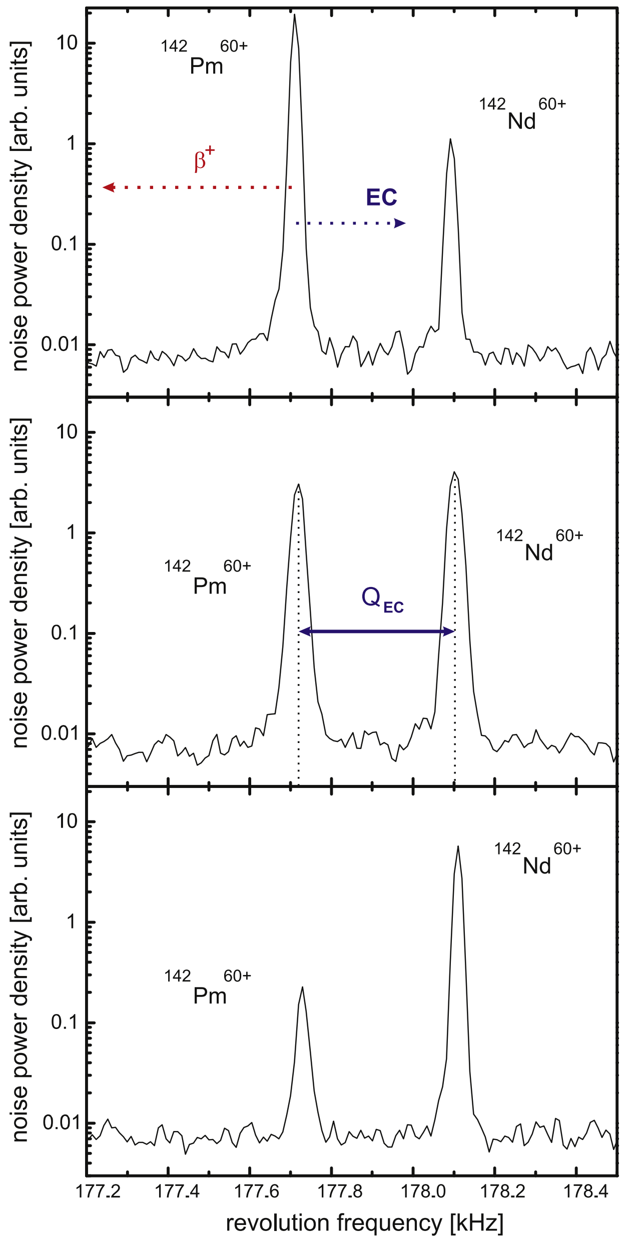

Fig. 1. (Color online.) Time evolution of intensities of hydrogen-like $^{142}Pm^{60+}$ parent ions and the fully-ionized $^{142}Nd^{60+}$ daughter ions stored in the ESR. The intensity is plotted on a logarithmic scale. The upper, middle and lower panels correspond to three Schottky frequency spectra averaged over about 2.6 seconds and which are taken at the beginning, at the middle and at the end of a measurement cycle, respectively.

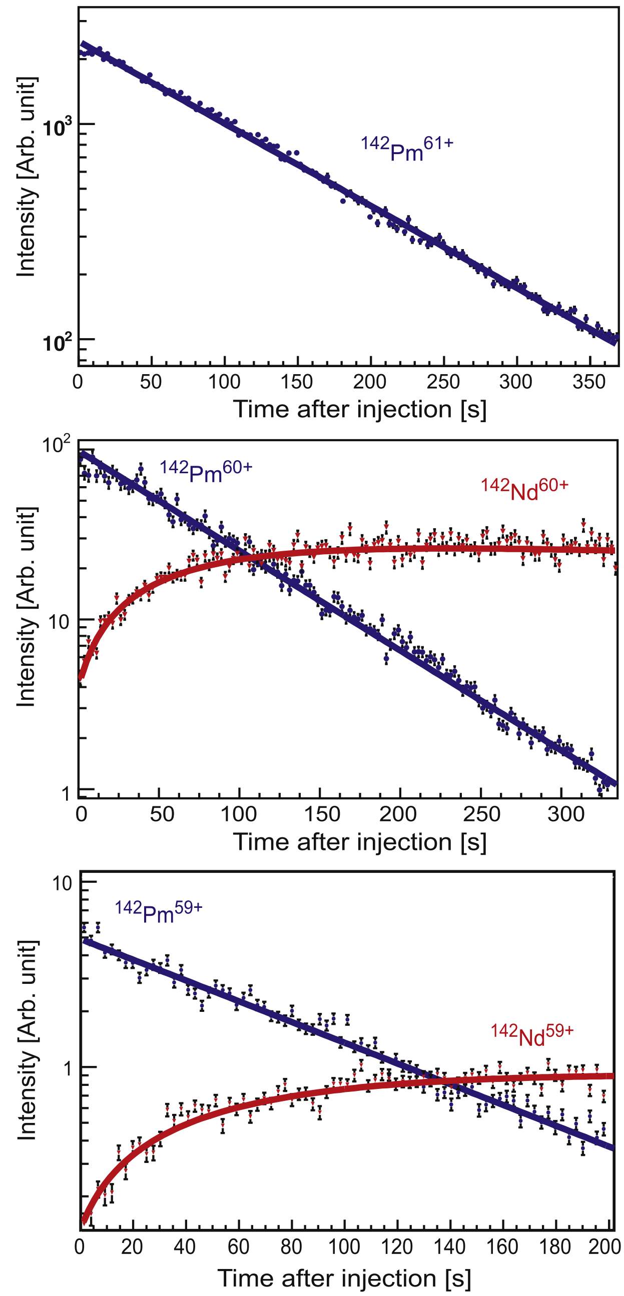

Fig. 2. (Color online.) An example of a measured decay curve of fully-ionized $^{142}Pm^{61+}$ ions is shown in the upper panel. Decay curves of H-like and He-like ^{142}Pm together with the corresponding growth curves of fully-ionized and H-like ^{142}Nd ions are illustrated in the middle and in the lower panel, respectively. Each time bin corresponds to about 2.6 s.

tinuum β^+ decay constant λ_{β^+}, and the loss constant λ_{loss} due to collisions with residual gas atoms or pick-up of electrons in the electron cooler:

$$\lambda = \lambda_{\text{EC}} + \lambda_{\beta^+} + \lambda_{\text{loss}}. \tag{2}$$

It is clear that for fully-ionized ^{142}Pm nuclei $\lambda_{\text{EC}} = 0$ due to the absence of bound electrons.

Several measurements of the decay of $^{142}Pm^{59+}$, $^{142}Pm^{60+}$, and $^{142}Pm^{61+}$ ions have been performed. Examples of the decay curves of ^{142}Pm ions in the three charge states and, for the case of H- and He-like ^{142}Pm ions, also the corresponding growth curves of the ^{142}Nd daughter ions are illustrated in Fig. 2.

Decay curves of the parent ions have been fitted with an exponential function:

$$N_{\text{Pm}}(t) = N_{\text{Pm}}(0) \cdot e^{-\lambda t}, \tag{3}$$

where $N_{\text{Pm}}(t)$ and $N_{\text{Pm}}(0)$ is the number of parent ions at the time t after injection and at $t = 0$, the time of injection, respectively. The growth of the number of daughter ^{142}Nd ions is determined by the EC decay of the exponentially decreasing number of ^{142}Pm ions. The daughter ions are stable and their loss is solely determined by the λ_{loss}. Therefore, the growth of the number of fully-ionized and H-like ^{142}Nd ions as a function of time t, $N_{\text{Nd}}(t)$ is described by

Table 1
Measured β^+ and EC decay constants (in the rest frame of the ions) obtained for fully-ionized, hydrogen-like, and helium-like ^{142}Pm ions for two different cooler currents 50 mA and 250 mA. Measurements of β^+-decay constant of fully-ionized ^{142}Pm ions have been performed only with cooler current of 250 mA.

$I_c = 50$ mA			
Ion	λ_{β^+} [s^{-1}]	λ_{EC} [s^{-1}]	EC/(β^+ + EC)
$^{142}Pm^{60+}$	0.0127(10)	0.0051(2)	(28.7±2.5)%
$^{142}Pm^{59+}$	0.0132(16)	0.0033(4)	(20.0±3.4)%
$I_c = 250$ mA			
Ion	λ_{β^+} [s^{-1}]	λ_{EC} [s^{-1}]	EC/(β^+ + EC)
$^{142}Pm^{61+}$	0.0123(7)	–	–
$^{142}Pm^{60+}$	0.0126(3)	0.0052(2)	(29.1±1.6)%
$^{142}Pm^{59+}$	0.0141(6)	0.0036(1)	(20.3±1.1)%

the following equation:

$$\frac{dN_{\mathrm{Nd}}(t)}{dt} = \lambda_{\mathrm{EC}} \cdot N_{\mathrm{Pm}}(t) - \lambda_{\mathrm{loss}} \cdot N_{\mathrm{Nd}}(t).$$

From this equation the following fit function can be obtained [13]:

$$N_{\mathrm{Nd}}(t) = N_{\mathrm{Pm}}(0) \cdot \frac{\lambda_{\mathrm{EC}}}{\lambda - \lambda_{\mathrm{loss}}} \cdot \left[e^{-\lambda_{\mathrm{loss}} t} - e^{-\lambda t}\right] + N_{\mathrm{Nd}}(0) \cdot e^{-\lambda_{\mathrm{loss}} t}. \tag{4}$$

The time modulated EC-decay of H-like ^{142}Pm ions with a period of about 7 s and an amplitude of 0.23 has been reported in [32]. However, it can be shown [33] that such a time modulation of the EC-decay rate cannot be observed in the present experiment. The modulation amplitude of 23% which is clearly seen in the measured $dN_{\mathrm{EC}}(t)/dt$ spectra in Ref. [32] corresponds to the amplitude of less than 1% in the measured here integrated curves $N_{\mathrm{Pm}}(t)$ and $N_{\mathrm{Nd}}(t)$. This effect is much smaller than the statistical uncertainties of individual data points.

The fits were done with the MINUIT package [34] using the χ^2 minimization. The obtained reduced χ^2_{min} values lie in the range $2 \geqslant \chi^2_{\mathrm{min}} \geqslant 4$. These large reduced χ^2_{min} values suggest that the scatter of the fitted data points is larger than their statistical uncertainties. The origin of this large scatter is presently unclear. We followed the standard way for the analysis of such data, described in detail in Ref. [35]. The uncertainties of the fit parameters have been increased by a factor $\sqrt{\chi^2_{\mathrm{min}}}$, that is by 40–100%.

In the present experiment we applied two different currents of the cooler electrons. The electron currents were 50 mA and 250 mA. They affect significantly the λ_{loss} constant (losses due to the pick-up of electrons in the cooler scale linearly with the cooler current, whereas the losses due to collisions with the rest gas atoms are independent on the cooler current).

The decay constants presented in Table 1 have been evaluated from about a hundred of injections and give consistent results. The averaged values for the λ_{EC} and λ_{β^+} decay constants converted to the rest frame of ions (relativistic Lorentz factor $\gamma = 1.43$) are presented in Table 2. As expected, the mean loss constant $\lambda_{\mathrm{loss}} = 0.00050(7)$ s^{-1} is larger for the higher electron current of 250 mA. The loss constant for the 50 mA electron current amounts to $\lambda_{\mathrm{loss}} = 0.00021(15)$ s^{-1}. The loss constants for a given electron current value are within the error bars the same for the studied charge states of ^{142}Nd and ^{142}Pm ions.

As can be seen from Table 2, the λ_{β^+} decay constant is within the error bars independent from the degree of the ionization. The ratios of the λ_{β^+} for the neutral atom [31] to the λ_{β^+} measured for bare, H-like and He-like ^{142}Pm ions are 1.07(7), 1.05(5) and 0.95(5), respectively. This is expected from the theory, since the electron screening modifies the β^+ decay rate by less than 3% in fully-ionized nuclei relative to neutral atoms [1,36].

Table 2
The averaged β^+ and EC decay constants (in the rest frame of the ions) determined for fully-ionized, hydrogen-like, and helium-like ^{142}Pm ions. The data for the neutral atom are taken from Ref. [31].

Ion	λ_{β^+} [s^{-1}]	λ_{EC} [s^{-1}]	EC/(β^+ + EC)
$^{142}Pm^{61+}$	0.0123(7)	–	–
$^{142}Pm^{60+}$	0.0126(3)	0.0051(1)	(29.0±1.3)%
$^{142}Pm^{59+}$	0.0139(6)	0.0036(1)	(20.2±1.0)%
$^{142}Pm^{0+}$	0.0132(5)	0.0039(5)	(22.9±2.7)%

The ratio of the EC decay constants of H-like and He-like ions is

$$\lambda^{\mathrm{H}}_{\mathrm{EC}}/\lambda^{\mathrm{He}}_{\mathrm{EC}} = 1.44(6).$$

This ratio is in excellent agreement with the results obtained in the EC-decay measurements of H-like and He-like ^{140}Pr ions [14], where the corresponding ratio of the decay constants is 1.49(8).

It has been shown in Refs. [14,16,17] that in order to understand the observed EC decay rates in H-like and He-like ions, one has to take into account the conservation of the total angular momentum of the nucleus-lepton system. Here, we shortly summarize the main points. For the extensive theoretical calculations we refer to Refs. [16,17], where a general formula is derived relating the electron capture rates in H-like and He-like systems for Gamow–Teller transitions $I_i \to I_i - 1$:

$$\lambda^{\mathrm{H}}_{\mathrm{EC}} = \lambda^{\mathrm{He}}_{\mathrm{EC}} \cdot \frac{2I_i + 1}{2F_i + 1}, \tag{5}$$

where I_i is the nuclear spin in the initial state (i) and F_i is the total angular momentum of the nucleus plus leptons system.

In the initial state (i), the hydrogen-like ^{142}Pm nucleus with spin $I_i = 1$ and a single bound electron with spin $s = 1/2$ can be present in two hyperfine states with total angular momenta F_i: $F_i = I_i - s = 1/2$ and $F_i = I_i + s = 3/2$. In the final state (f), however, there is only one value of F_f possible, $F_f = 1/2$, which results from the sum of the zero angular momentum of the ^{142}Nd nucleus $I_f = 0$ and the spin $s = 1/2$ of the emitted electron-neutrino. Only transitions between $F_i = F_f = 1/2$ conserve the total angular momentum and are, therefore, allowed. The decay from the $F_i = 3/2$ state requires that the emitted neutrino carries away orbital angular momentum, which corresponds to a much slower forbidden decay. The magnetic moment of ^{142}Pm has been estimated to be positive $\mu \approx +2.5\mu_{\mathrm{N}}$ [37], which means that $^{142}Pm^{60+}$ ions are stored – due to a short relaxation time of a few ten milliseconds – in the $F_i = 1/2$ hyperfine ground state.

Two electrons in the helium-like ion couple to spin 0. Therefore, in this decay only the transitions between $F_i = F_f = 1$ are allowed. This means that only particular projections of the spin of the captured electron can contribute to the allowed decay.

By inserting the $I_i = 1$ and $F_i = 1/2$ values for ^{142}Pm nucleus into Eq. (5), we obtain the ratio of EC decay probabilities of 1.5, which is in excellent agreement with present experimental results. Although the re-population of upper hyperfine states has not been observed in storage ring experiments [38], this agreement can be used as an additional justification for the assumption above that the H-like ions are mainly stored in the $F_i = 1/2$ hyperfine ground state.

4. Summary

In summary, we have performed accurate measurements of the β^+ and EC-decay constants of fully-ionized, H-like and He-like

^{142}Pm ions. We emphasize, that this is the second experimental study of β^+ and EC-decay of H-like, and He-like ions. The obtained results show that the electron capture decay rate in the H-like ions is by about 50% larger than in the He-like ions, which is in agreement with the only available previous result for ^{140}Pr ions [14]. It is obvious that the present result disagrees to the often used simple scaling of the EC decay rate with the number of s-electrons weighted by the third power of the principal quantum number. It is shown that in the two-body β-decay it is necessary to take into account the conservation of the total angular momentum, since only particular spin orientations of the nucleus and of the captured electron can contribute to the allowed decay.

It is important to note that there have been many measurements of EC decay rates performed in neutral atoms from different electron orbitals, K, L, M-shells, by detecting the characteristic X-rays following the decay [39]. In all these studies, however, the influence of all other bound electrons has to be taken into account. In the storage ring experiments we are able to study pure one- or two-electron systems in well-defined quantum states.

The two-body β-decay studies of highly-charged ions will be extended in future with measurements of other nuclear species with different initial and final spins [40]. It is of particular interest to investigate for the first time the EC-decay of Li-like ions.

Acknowledgements

Fruitful discussions with Leonid Batist, Klaus Blaum, Jan Kurcewicz, Agatino Musumarra, Kohji Takahashi, and Iliya Tupitsyn are gratefully acknowledged. We thank the GSI accelerator team for the excellent technical support and we are in particular grateful to Karl-Heinz Behr, Adolf Brünle, and Christos Karagiannis for their technical help in preparing the experiment.

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